FORM 2

THE PATENTS ACT, 1970

(39 of 1970)

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The Patents Rules, 2003

COMPLETE SPECIFICATION

(See Section 10 and Rule 13)

Title of the Invention

A NOVEL LAM THROAT CAPTURING & PRELOADING MECHANISM FOR AUTONOMOUS CAPTURE OF NON-COOPERATIVE SPACECRAFT

Name and Address of the Applicant

INDIAN SPACE RESEARCH ORGANISATION

Department of Space, Antariksh Bhavan, New BEL Road, Bengaluru, Karnataka, India 560094

Nationality

A Government of India Organisation

Preamble to the Description

The following specification particularly describes the invention and the manner in which it is to be performed.

FIELD OF INVENTION

[0001] The present invention relates to On-Orbit Servicing (OOS), specifically a servicer spacecraft with capabilities of capturing non-cooperative target to increase the life of existing spacecrafts in Geostationary Equatorial Orbit (GEO) and Low Earth orbit (LEO).

BACKGROUND OF INVENTION

[0002] On-Orbit Servicing (OOS) refers to the practice of maintaining, repairing, upgrading, and repositioning spacecraft directly in space, which significantly extends their operational life and functionality. By using advanced robotics and autonomous systems, OOS allows for tasks like refueling, fixing issues, and updating technology without the need for launching new spacecrafts. Additionally, OOS can provide life extension to aging, non-cooperative spacecraft that were not originally designed for servicing, by using specially equipped servicer spacecrafts to dock and perform necessary maintenance or adjustments. This not only saves costs but also reduces space debris, making space operations more sustainable. With successful missions already demonstrating its potential, OOS is becoming an essential capability for both government and commercial space missions, ensuring spacecrafts continue to support communication, navigation, and scientific endeavors efficiently.

[0003] The technology currently available to carry out a successful OOS mission for an existing non-cooperative spacecraft (client spacecraft) in LEO or GEO involves capturing the spacecraft through the Liquid Apogee Motor (LAM) throat. In this method, the client spacecraft is captured by inserting a probe mounted on the servicer spacecraft into the liquid apogee engine at the aft end of the client spacecraft. The liquid apogee engine guides the probe, which then moves slowly through the throat of the engine to capture the spacecraft. The probe retracts, pulling frames against the ring to lock and preload the crafts together. MEV-1 with Intelsat 09 & MEV-2 with Intelsat 10 are classic examples of a LAM throat capture docking missions which have been

successfully flown in the recent past. Figure 1 shows the conceptual illustrations of LAM throat capture docking of MEV-1 with Intelsat 09.

[0004] The prior art "Apollo Docking Mechanism" discloses a first probe and drogue docking mechanism, which was an improvement over the Gemini Agena docking mechanism. It comprises an extending probe that performs docking with the drogue present in the client spacecraft. This is a non-autonomous docking system wherein the crew would maneuver the servicer spacecraft to proximity and close in for docking in step-based procedures. Additionally, there is no disclosure on the use of shape memory alloy (SMA) for the capture and docking system.

[0005] The prior art "Soyuz Docking Mechanism" discloses a similar non-autonomous type of probe and drogue docking mechanism. Before docking, a crewman in the chaser module activates a switch to extend the probe until it reaches the bottom of the drogue through the guided socket. Once the probe is in contact with the bottom of the drogue, three capture latches in the probe are released to hold the two spacecraft together. There is no disclosure on the use of shape memory alloy (SMA) for the capture and docking system.

[0006] The prior art "X-ray Solar Monitor (XSM) filter wheel drive mechanism in Chandrayaan-2 orbiter" discloses the use of a shape memory alloy (SMA) as an actuator to provide rotational motion to the filter wheel. The XSM filter wheel drive mechanism comprises three SMA wires configured at 120° to each other and mounted at a 3.5 mm offset distance with respect to the filter wheel rotation axis. Due to this offset mounting, the linear force exerted by SMA wire contraction induces a torque about the wheel rotation axis, causing the filter wheel to rotate. There is no disclosure regarding a capture and docking system for client and servicer spacecrafts.

[0007] The prior art "SMA mechanism for CubeSats" discloses a release and retention device controlled by an SMA-activated pin puller to disengage the release plate from the hooks holding the solar arrays. Once released, the SMA hinge is passively enabled

to move to the deployed state. This mechanism is used for the hold-down and deployment of appendages. However, there is no disclosure regarding a capture and docking system for client and servicer spacecrafts.

[0008] The prior art "MEV-1 with Intelsat 901 & MEV-2 with Intelsat 10-02" features both a compliance mechanism and a docking mechanism on the servicer spacecraft. The compliance mechanism includes a ball-screw actuated sliding stage and an eddy current damper with a rack and pinion assembly, which actuates a compliant probe with spring-loaded fingers. This probe is inserted into the LAM of the client spacecraft during the approach motion. The docking mechanism incorporates abutment pads/rigid stanchions that interface with the launcher interface ring of the client spacecraft. When preload is applied to these pads/stanchions through the probe retraction, the docking mechanism maintains a rigid docked interface under loads induced by thrusting maneuvers of the combined spacecraft or by on-orbit servicing operations, as shown in Figure 2.

[0009] The prior art "SMART-OLEV (Orbital Life Extension Vehicle)" describes a chaser spacecraft that docks with a client spacecraft to take over Attitude and Orbit Control System (AOCS) tasks and/or perform orbital maneuvers, as shown in Figure 3. During the capturing phase, the boom speed is adjusted based on the penetration depth and the distance of the capture tool tip from the nozzle wall. Additionally, the contact switches of the capture tool are monitored. When these switches indicate that the tip is fully inserted into the nozzle, the crown locking mechanism of the capture tool is activated, and the boom movement is stopped. Once the client is locked, the boom is commanded to retract. If the client pushes against the client support brackets, the boom retraction is autonomously stopped. Using a dedicated command, the boom is then slowly retracted in small steps until the required boom tension is achieved.

[0010] However, none of the prior arts disclose features such as deployable frames designed to capture non-cooperative spacecraft with both small and large inertia.

Additionally, they do not address the capability to capture both GEO (1194 mm Launch Adapter Ring (LAR)) and LEO (937 mm LAR) type spacecraft interface rings. Furthermore, the prior arts have several potential drawbacks, including:

- Fixed/rigid stanchions/frames for final preloading of client with servicer spacecraft which enhances the overall stowed volume and results in over design of stanchions to meet stowed frequency requirements of the spacecraft.
- Soft capture mechanism is not available which may result in separation or docking failure of client and servicer spacecraft during initial contact of probe with LAM
- Compliant probe consists of a balls screw driven through actuator and an eddy current damper which increase mass and complexity in the mechanism.

[0011] In the present invention, the frames are kept folded during launch, similar to other deployable appendages, and are released once in orbit to perform dual operations: initial soft capture of the LAM and final preloading of the client spacecraft with the servicer spacecraft using a single actuator. An additional hold-down system is avoided by employing a non-back-drivable gear assembly driven by an actuator, which reduces mass, launch costs, and enhances system reliability. The proposed compliant probe features flexures driven by SMA wires, making the mechanism compact and simple. The probe is retracted until the desired preload between the spacecraft is achieved. This preload is monitored via a contact switch mounted on frames, which are prepositioned to actuate at the design preload, thereby confirming the required composite stiffness.

OBJECT OF INVENTION

[0012] Some of the objects of the present disclosure, which at least one embodiment herein satisfies, are as follows:

[0013] An object of the present disclosure is to develop a novel LAM Throat Capturing and Preloading (LTCP) mechanism for Indian On-Orbit Servicing (OOS) of existing

non-cooperative spacecraft reaching end-of-life (EOL) for life extension with optimized resources such as mass, power, and space.

[0014] Another object of the present invention is that the proposed LTCP mechanism has the ability to capture both GEO (1194 mm LAR) and LEO (937 mm LAR) types of spacecraft interface rings.

[0015] Yet another object of the present invention is to design the deployable frames to be kept folded during launch, similar to other deployable appendages, and to release them once in orbit to perform the necessary operations efficiently.

[0016] Yet another object of the present invention is to develop a mechanism that can perform both initial soft capture of the LAM and final preloading of the client spacecraft with the servicer spacecraft using a single actuator.

[0017] Yet another object of the present invention is to avoid the need for an additional hold-down system by employing a non-back-drivable gear assembly driven by an actuator, thereby reducing mass, launch costs, and enhancing overall system reliability.

[0018] Yet another object of the present invention is that the proposed LTCP mechanism incorporates the compliant probe featuring flexures driven by SMA wires, ensuring a compact and simple design.

[0019] Yet another object of the present invention is to develop a probe retraction system that achieves the desired preload between the spacecraft, monitored via a contact switch mounted on frames that actuate at the design preload, confirming the required composite stiffness.

[0020] Other objects and advantages of the present disclosure will be more apparent from the following description, which is not intended to limit the scope of the present disclosure.

SUMMARY OF THE INVENTION

[0021] For OOS mission, new technology needs to be developed to servicer spacecrafts with the capability to capture non-cooperative targets, thereby increasing the life of existing spacecrafts in GEO/LEO. The basic idea is to provide life extension to aging non-cooperative existing spacecraft while still utilizing their payload services. A servicer spacecraft, equipped with capture technology, approaches the client spacecraft nearing end of life at low velocity using closed-loop guidance with proximity sensors in the loop to enhance its life.

[0022] The present invention introduces a novel LAM Throat Capturing and Preloading (LTCP) mechanism for the autonomous capture of non-cooperative spacecraft. This mechanism is capable of interfacing with the LAM of the client spacecraft to allow a servicer spacecraft to dock with a client spacecraft that has no special docking features. The servicer spacecraft, equipped with this mechanism, possesses the ability to autonomously capture, preload, and release different categories of existing client spacecraft multiple times for life extension. The LTCP includes a cone shaped compliant probe with a flexure for locking and unlocking mechanism through the SMA wire ropes. This probe is inserted into the LAM of the client spacecraft by the approach motion of the servicer spacecraft. When the probe tip has passed beyond the throat of the LAM, the flexure extends to trap the wall of the LAM, thus achieving capture. The preloading stage of docking is achieved by retracting the probe to pull the two spacecraft rings together against frames mounted on the servicer spacecraft.

[0023] The method for the autonomous capture of non-cooperative spacecraft using the novel LTCP mechanism involves several key steps. When the mechanism entry sensor (MES) on the servicer spacecraft indicates that the two spacecraft are within the capture envelope, the deployable frames mounted on the servicer spacecraft are actuated to softly capture the nozzle/LAM of the client spacecraft. This soft capture ensures that the spacecraft do not move away from each other due to docking forces. Next, a

telescopic mechanism extends the compliant probe, which is then inserted into the LAM of the client spacecraft. Once the probe tip passes beyond the throat of the LAM, the flexure on the probe tip is actuated using SMA wire ropes. The probe moves in a guided manner through the throat of the engine inside the LAM, with its cone shape providing self-alignment capability and enabling the capture of the spacecraft. Once the probe is engaged, the frames holding the throat are disengaged from the LAM surface and made vertically rigid. The probe then uses the telescopic extendable and retractable mechanism to retract the client spacecraft towards the frames mounted on the servicer spacecraft, locking/preloading the crafts together. The probe is retracted until the desired preload is achieved between the spacecraft. This preload is monitored through a force sensor mounted on the frames, prepositioned to actuate at the desired preload. The mechanism is also configured to release and separate the two spacecraft on command and is capable of repeating these operations multiple times if required.

BRIEF DESCRIPTION OF THE ACCOMPANYING DRAWINGS

[0024] The other objects, features and advantages will occur to those skilled in the art from the following description of the preferred embodiment and the accompanying drawings in which:

[0025] **Figure 1** is a conceptual illustration of LAM throat capture docking of MEV-1 with Intelsat 09, according to an embodiment of the existing prior-art.

[0026] **Figure 2** is a schematic representation of the capture probe used in the on-orbit servicing operations of MEV-1 with Intelsat 09, according to an embodiment of the existing prior-art.

[0027] **Figure 3** is a conceptual illustration of the locking crown and capturing concept of SMART-OLEV, according to an embodiment of the existing prior-art.

[0028] **Figure 4** is a schematic representation of the overall configuration of novel LTCP mechanism, according to an embodiment of the present invention.

[0029] **Figure 5** is a schematic representation of the concept of soft capture of the LAM of the client spacecraft by the servicer spacecraft, according to an embodiment of the present invention.

[0030] **Figure 6** is a schematic representation of the lead screw operated extendable and retractable telescopic unit, according to an embodiment of the present invention.

[0031] **Figure 7** is a schematic representation of the cone shaped compliant probe unit, according to an embodiment of the present invention.

[0032] **Figure 8** is a schematic representation of the concept of preloading of the client spacecraft onto the servicer spacecraft for carryout the OOS functions, according to an embodiment of the present invention.

[0033] **Figure 9** is a conceptual illustration of the various phases involved in the method for the autonomous capture of non-cooperative spacecraft using the novel LTCP mechanism, according to an embodiment of the present invention.

LIST OF REFERENCE NUMERALS

100 – LTCP mechanism

101 – Servicer spacecraft

102 – Client spacecraft

103 – Robotic arm

104 – Stereo cameras

105 – MES sensors

120 – LAM capturing unit

121 – Deployable frames

122 – LAM

123 – Frame actuation drive system

140 – Telescopic unit

141 – Actuator

142 – Lead screw

143 – First tube

144 – First tube lead nut

145 – Latch pins

146 – Second and succeeding tubes

147 – Second and succeeding tube lead nuts

148 – Shank region of the lead screw

160 – Compliant probe unit

161 – Cone shaped probe

162 – Contact switch

163 – Probe flexure

164 – Flexure spring

165 – Wire rope

166 – SMA wire

180 – Preloading unit

181 – Preloading surface

182 – Force sensor

DETAILED DESCRIPTION OF THE INVENTION

[0034] The present invention may be embodied in several forms, and the details of embodiments of the present invention will be described in the following content with figures. The embodiments described below with reference to the drawings are merely illustrative of the technical solutions of the present disclosure but are not to be construed as limited to the technical solutions of the present disclosure.

[0035] The terms and words used in the following description and claims are not limited to the bibliographical meanings but are merely used by the inventor to enable a clear and consistent understanding of the invention. Accordingly, it should be apparent to those skilled in the art that the following description of the present invention

is provided for illustration purposes only and not for the purpose of limiting the invention as defined by the appended claims. As used in the description of the invention and the appended claims, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise.

[0036] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure pertains. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0037] The present invention introduces a series of groundbreaking embodiments designed to autonomous capture of non-cooperative spacecraft using the novel LAM Throat Capturing and Preloading (LTCP) mechanism.

[0038] In the primary embodiment, the present invention discloses a novel LAM Throat Capturing and Preloading (LTCP) mechanism for Indian On-Orbit Servicing (OOS) of existing non-cooperative spacecraft reaching end-of-life (EOL) for life extension with optimized resources such as mass, power, and space. This is achieved by integrating four essential units in the LTCP mechanism in the servicer spacecraft: the LAM capturing unit, the telescopic unit, the compliant probe unit, and the preloading unit. The LAM capturing unit is responsible for identifying the client spacecraft within the capture envelope and softly capturing the nozzle/LAM of the client spacecraft. The telescopic unit is used to insert the compliant probe unit into the LAM of the client spacecraft during its extendable motion and pull the client spacecraft towards the frames mounted on the servicer spacecraft during its retractable motion. The compliant probe unit engages and disengages the LAM of the client spacecraft through the probe flexure activated by the SMA wire ropes. The preloading unit ensures the designed

preload while engaging the client spacecraft against the servicer spacecraft through the force sensor and cuts off the retraction motion of the telescopic unit. These units collectively ensure the autonomous capture of non-cooperative spacecraft that have no special docking features.

[0039] In another embodiment, the present invention focuses on autonomous capture of non-cooperative spacecraft using the novel LAM Throat Capturing and Preloading (LTCP) mechanism in both GEO (1194 mm LAR) and LEO (937 mm LAR) types of spacecraft interface rings. This feature enables the servicer spacecraft to capture the client spacecraft with smaller as well as larger inertia.

[0040] In yet another embodiment, the present invention is equipped with a robotic arm and two stereo cameras, one configured with the robotic arm and the other with the servicer spacecraft base. These features enable the servicer spacecraft to recognize the orientation of the client spacecraft before capturing and monitor the engagement orientation of the servicer spacecraft with the client spacecraft during and after the engagement. It ensures a safe distance capturing of interface ring of client spacecraft through the servicer spacecraft. Moreover, the stereo cameras are equipped with lighting features to illuminate the client spacecraft when it is in shadow or within the apogee engine nozzle, providing visual guidance during the final approach from a 3-meter circumference. Furthermore, the novel LTCP mechanism is equipped with an MES sensor on the deployable frames to indicate that the two spacecraft are within the capture envelope and actuate the deployable frames mounted on the servicer spacecraft to initiate the soft capture of the LAM of the client spacecraft.

[0041] In yet another embodiment of the present invention, the LTCP mechanism is equipped with deployable frames kept folded (stowed configuration) during launch, similar to other deployable appendages, and released once in orbit to perform the necessary operations efficiently, resulting in compact storage. The deployable frames are designed to avoid the need for an additional hold-down system by employing a non-

back-drivable gear assembly driven by an actuator, thereby reducing mass, launch costs, and enhancing overall system reliability. Moreover, the deployable frames can perform both the initial soft capture of the LAM and the final preloading of the client spacecraft with the servicer spacecraft using a single actuator. This soft capture ensures that the spacecraft do not move away from each other due to docking forces. Furthermore, the MES sensor in the deployable frames provides the cue for initiating soft capture in a non-contact manner.

[0042] In yet another embodiment of the present invention, the novel LTCP mechanism is equipped with a telescopic unit to actuate the compliant probe in an axial direction, thereby inserting the compliant probe into the LAM of the client spacecraft for latching purposes. Once the probe flexure latches inside the LAM throat, the telescopic unit is notified through a contact switch and initiates the retraction motion while simultaneously disengaging the deployable frames holding the throat from the LAM surface and making them vertically rigid. This allows the LTCP mechanism to pull the client spacecraft almost parallel towards the servicer spacecraft's preloading surface located on the deployable frames mounted on the servicer spacecraft. The entire process is monitored through the two stereo cameras present in the LTCP mechanism.

[0043] In yet another embodiment of the present invention, the entire telescopic unit utilizes a lead screw and lead nut drive mechanism to convert rotary motion into linear motion and to axially move the compliant probe toward the LAM. When the lead screw receives rotational drive from the actuator, it actuates the first tube to move axially upwards (extension motion) as the lead nut in the first tube engages with the lead screw. Each inner tube in the telescopic unit features three latch pins on its outer surface and slides against the inner wall of the next consecutive tube, synchronously latching and unlatching to transfer the linear motion to the next cylinder. For example, once the first tube's lead nut reaches the end of the lead screw, the three latch pins (synchronization mechanism) latch it with the second tube. At the same time, the lead nut in the second

tube engages with the lead screw, causing the second tube to move axially upwards. This sequence is repeated until the last tube reaches the end of the lead screw.

[0044] For retraction motion, the direction of the lead screw rotation is reversed by the actuator, causing the last tube to move axially downwards as the lead nut in the last tube engages with the lead screw. Once the lead nut of the last tube reaches the shank portion of the lead screw, the latch pins locked with the last tube unlatch, and the lead nut in the next tube engages with the lead screw and moves vertically downwards. This sequence is repeated until the first tube reaches the bottom end threaded portion of the lead screw. Accomplishing these functions in synchronization with the lead screw-lead nut movement and the mechanical latch pin is the ingenious and most critical aspect of this invention. Therefore, maintaining good positional accuracy of these elements during fabrication and assembly is crucial for flawless performance. The latch pins play a vital role and perform the following functions sequentially:

- Assist in latching the tubes to one another in the stowed mode.
- Unlatch the tubes in a defined sequence and latch the extended tube to its next outer tube during extension.
- Unlatch the retracting tube and latch the tube during retraction.

[0044] In yet another embodiment of the present invention, the compliant probe is rigidly mounted on the telescopic unit to be inserted into the LAM of the client spacecraft for efficient latching and unlatching of the client spacecraft with the servicer spacecraft. Once the telescopic unit actuated the compliant probe moves in a guided manner through the throat of the engine inside the LAM, with its ingenious cone shape providing self-alignment capability and gets indication from the MES sensors. Once the compliant probe tip passes beyond the throat of the LAM, the probe flexure latches with the LAM throat against the flexure spring force. The contact switch in the compliant probe indicates successful latching to the actuator, prompting the actuator to reverse its rotation direction. This initiates the retraction movement of the telescopic unit while disengaging the deployable frames holding the LAM of the client spacecraft

and making them vertically rigid. A single actuator drives both the telescopic unit and the deployable frames through the frame actuation drive systems. Once latching is confirmed by the contact switch, the LTCP mechanism pulls the client spacecraft parallel to the servicer spacecraft's preloading surface located on the deployable frames. After completing the OOS operations, the SMA wire in the compliant probe is activated to pull the wire rope, actuating the flexure spring to unlatch the probe flexure from the LAM throat, ensuring a compact and simple design. The LTCP mechanism can release and separate the two spacecraft on command and is capable of repeating these operations multiple times if required.

[0045] In yet another embodiment of the present invention, the preloading unit monitors the preload when the client spacecraft butts onto the preloading surface of the deployable frames. The preloading surfaces are equipped with force sensors that measure the amount of preload. Once the desired preload is achieved, the sensors signal the actuator to stop the retractable motion of the compliant probe. This ensures the proper parallel orientation of the client spacecraft onto the servicer spacecraft, thereby initiating the On-Orbit Servicing (OOS) of existing non-cooperative spacecraft reaching end-of-life (EOL) for life extension with optimized resources such as mass, power, and space. Additionally, the LTCP mechanism can push the client spacecraft away from the servicer spacecraft after completing the OOS and release the client spacecraft, eliminating the need for a separate release mechanism. Thus, the LTCP mechanism can autonomously capture, preload, and release the client spacecraft repeatedly as required.

[0046] Overall, these embodiments provide a novel LAM Throat Capturing and Preloading (LTCP) mechanism for On-Orbit Servicing (OOS) to extend the life of non-cooperative spacecraft nearing end-of-life. The LTCP mechanism, integrated into a servicer spacecraft, includes deployable frames, a telescopic unit, a compliant probe, and a preloading unit. It autonomously captures the client spacecraft by soft capturing the LAM, inserting the compliant probe for secure latching, and retracting the client

spacecraft for preloading. The mechanism ensures efficient use of mass, power, and space, and can repeatedly capture, preload, and release the client spacecraft as needed, enabling effective OOS operations.

[0047] With reference to the Figures 1 – 8, the novel LAM Throat Capturing and Preloading (LTCP) mechanism (100) according to the present invention comprising the LAM capturing unit (120), the telescopic unit (140), the compliant probe unit (160), and the preloading unit (180).

[0048] With reference to Figure 4, the LTCP mechanism (100) configured with the servicer spacecraft (101) has the ability to autonomously capture the non-cooperative client spacecraft (102) to perform On-Orbit Servicing operations. This is achieved by the functional integration of the LAM capturing unit (120), the telescopic unit (140), the compliant probe unit (160), and the preloading unit (180). The LAM capturing unit (120) comprises at least three deployable frames (121) mounted on the servicer spacecraft (101) and operated by the actuator (141) through the frame actuation drive system (123) for the initial soft capture of the LAM (122) of the client spacecraft (102). The telescopic unit (140) comprises plurality of nested hollow tubes (143, 146), each smaller in diameter than the previous one, allowing them to fit inside one another in a concentric manner, and a central lead screw (142). The lead nut (144, 147) in each tube engages with the lead screw (142) to provide extendable and retractable motion to the compliant probe unit (160), with the support of three latch pins (145) located on the outer surface of each inner tube. The telescopic unit (140) is used to insert the compliant probe unit (160) into the LAM (122) of the client spacecraft (102) during its extendable motion and to pull the client spacecraft (102) towards the deployable frames (121) mounted on the servicer spacecraft (101) during its retractable motion.

[0049] The compliant probe unit (160) rigidly mounted on the telescopic unit (140) comprises a cone-shaped probe (161) featuring a probe flexure (163) to latch and unlatch the throat of the LAM (122) of the client spacecraft (102). Additionally, the

compliant probe unit (160) is configured with a contact switch (162) to signal the latching and an SMA wire (166) to pull the wire rope (165), thereby actuating the flexure spring (164) to unlatch the probe flexure (163) from the LAM (122) throat. The preloading unit (180) comprises a preloading surface (181) on the deployable frames (121), mounted with a force sensor (182) to ensure the designed preload while engaging the client spacecraft (102) against the servicer spacecraft (101) and to cut off the retraction motion of the telescopic unit (140). Thus, the LTCP mechanism (100) can autonomously capture, preload, and release the client spacecraft repeatedly as required.

[0050] Additionally, the LTCP mechanism (100) is equipped with a robotic arm (103) and two stereo cameras (104), one configured with the robotic arm (103) and the other with the servicer spacecraft (101) base. These features enable the servicer spacecraft (101) to recognize the orientation of the client spacecraft (102) before capturing and monitor the engagement orientation of the servicer spacecraft (102) with the client spacecraft (101) during and after the capturing. Moreover, the stereo cameras (104) are equipped with lighting features to illuminate the client spacecraft (102) when it is in shadow or within the apogee engine nozzle, providing visual guidance during the final approach from a 3-meter circumference. Moreover, the LTCP mechanism (100) is equipped with an MES sensor (105) on the deployable frames (121) to indicate that the two spacecraft (101, 102) are within the capture envelope and actuate the deployable frames (121) mounted on the servicer spacecraft (101) to initiate the soft capture of the LAM (122) of the client spacecraft (102).

[0051] With reference to Figure 5, the LAM capturing unit (120) mainly comprises at least three deployable frames (121) that are kept folded during launch and released once in orbit. The MES sensor (105) in the deployable frames (121) provides the cue for initiating soft capture in a non-contact manner. The deployable frames (121) are mounted on the servicer spacecraft (101) and operated by the actuator (141) through the frame actuation drive system (123) in a synchronized manner. When the actuator (141) rotates, all three deployable frames (121) move towards the nozzle/LAM (122)

of the client spacecraft (102) for soft capture. After latching the probe (161) into the throat of the LAM (122), the actuator reverses the rotational direction, causing all three deployable frames (121) to move outwards from the LAM (122) and become rigidly vertical for preloading purposes. Thus, the deployable frames (121) can perform both the initial soft capture of the LAM (122) and the final preloading of the client spacecraft (102) with the servicer spacecraft (101) using a single actuator (141).

[0052] With reference to Figure 6, the telescopic unit (140) comprises a plurality of nested hollow tubes (143, 146), each smaller in diameter than the previous one, allowing them to fit inside one another in a concentric manner, a central lead screw (142), and each tube (143, 146) is featured with a lead nut (144, 147) at the bottom. Additionally, all the tubes except the last tube are fitted with three latch pins (145) on the outer surface to assist in latching and unlatching the tubes to one another in the stowed configuration. The latch pins (145) are designed such that when the tube moves upwards, it latches to the next tube in contact, and when the tube moves downwards, it unlatches from the tube to which it was latched during the upward motion. During the extendable motion of the telescopic unit (140), the actuator (141) powers the lead screw (142) to rotate, causing the axial upward movement of the first tube (143) because the first tube lead nut (144) is engaged with the lead screw (142). Once the first tube lead nut (144) reaches the end of the lead screw (142), the three latch pins (145) in the first tube (143) latch with the second tube (146) while the second tube lead nut (147) engages with the lead screw (142), causing the second tube (146) to move axially upwards. This sequence is repeated until the last tube reaches the end of the lead screw (142).

[0053] During the retractable motion of the telescopic unit (140), the actuator (141) reverses the lead screw (142) rotation, causing the axial downward movement of the last tube (146) because the last tube lead nut (147) is engaged with the lead screw (142). Once the last tube lead nut (147) reaches the shank of the lead screw (148), the lead nut of the next-to-last tube engages with the lead screw (142) while the three latch pins

(145) unlatch from the last tube, causing the next-to-last tube to move axially downwards. This sequence is repeated until the first tube lead nut (144) reaches the bottom threaded portion of the lead screw (142). Thus, the telescopic unit (140) is used to insert the compliant probe unit (160) into the LAM (122) of the client spacecraft (102) during its extendable motion and to pull the client spacecraft (102) towards the deployable frames (121) mounted on the servicer spacecraft (101) during its retractable motion.

[0054] With reference to Figure 7, the compliant probe unit (160) rigidly mounted on the telescopic unit (140) comprises a cone-shaped probe (161) featuring a probe flexure (163) for efficient latching and unlatching of the throat of the LAM (122) of the client spacecraft (102). The ingenious cone-shaped probe (161) moves in a guided manner inside the LAM (122) of the client spacecraft (102) due to its self-alignment capability. Once the probe (161) passes beyond the throat of the LAM (122), the probe flexure (163) latched with the LAM (122) throat against the flexure spring (164) force. The contact switch (162) in the compliant probe unit (160) indicates the successful latching and initiates the retraction movement of the telescopic unit (140) simultaneously disengaging the deployable frames (121) capturing the LAM (122) of the client spacecraft (102) and making them vertically rigid for preloading. Once latching is confirmed by the contact switch (162), the LTCP mechanism (100) through the telescopic unit (140) pulls the client spacecraft (102) parallel to the servicer spacecraft (101) preloading surface (181) located on the deployable frames (121) for OSS operations. After completing the OOS operations, the SMA wire (166) in the compliant probe unit (160) is activated to pull the wire rope (165), thereby actuating the flexure spring (164) to unlatch the probe flexure (163) from the LAM (122) throat.

[0055] With reference to Figure 8, preloading unit (180) comprises a preloading surface (181) on the deployable frames (121), mounted with a force sensor (182) to monitors the preload when the client spacecraft (102) butts onto the preloading surface (181) of the deployable frames (121). Once the desired preload is achieved, the force sensors

(182) signal the actuator (141) to stop the retractable motion of the compliant probe unit (160) and ensures the proper parallel orientation of the client spacecraft (102) onto the servicer spacecraft (101) for initiating the On-Orbit Servicing (OOS) operations.

[0056] With reference to Figure 9, the method for the autonomous capture of non-cooperative spacecraft using the LTCP mechanism (100) involves four important phases. In phase 1, the robotic arm (103) with the stereo cameras (104) is used to recognize the orientation of the client spacecraft (102), and the MES sensor (105) on the deployable frames (121) indicates that the two spacecraft are within the capture envelope, preparing the servicer spacecraft (101) for capture. In phase 2, the actuator (141) powers the deployable frames (121) mounted on the servicer spacecraft (101) to move towards the LAM (122) of the client spacecraft (102) to initiate the soft capture. In phase 3, the telescopic unit (140) provides extendable motion to insert the compliant probe unit (160) into the throat of the LAM (122). The probe flexure (163) latches into the throat of the LAM (122) against the flexure spring (164) force, and the deployable frames (121) holding the LAM (122) are disengaged and made vertically rigid. Once the latching is confirmed by the contact switch (162), the telescopic unit (140) provides retractable motion to pull the client spacecraft (102) towards the deployable frames (121) mounted on the servicer spacecraft (101). In phase 4, the desired preload between the spacecrafts is ensured, and the force sensors (182) signal the actuator (141) to stop the retractable motion of the compliant probe unit (160), the On-Orbit Servicing (OOS) operations are initiated.

[0057] After completing the OOS operations, the SMA wire (166) in the compliant probe unit (160) is activated to pull the wire rope (165), thereby actuating the flexure spring (164) to unlatch the probe flexure (163) from the LAM (122) throat. This allows the LTCP mechanism (100) to push the client spacecraft (102) away from the servicer spacecraft (101), eliminating the need for a separate release mechanism. Thus, the LTCP mechanism can autonomously capture, preload, and release the client spacecraft repeatedly as required.

[0058] The basic idea of the present invention is to provide a novel LAM Throat Capturing and Preloading (LTCP) mechanism (100) for On-Orbit Servicing (OOS) to extend the life of non-cooperative spacecraft nearing end-of-life. The LTCP mechanism (100), integrated into a servicer spacecraft (101), comprises the LAM capturing unit (120), the telescopic unit (140), the compliant probe unit (160), and the preloading unit (180). It autonomously captures the client spacecraft (102) by soft capturing the LAM (122), inserting the compliant probe unit (160) for secure latching, and retracting the client spacecraft (102) for preloading. The mechanism ensures efficient use of mass, power, and space, and can repeatedly capture, preload, and release the client spacecraft (102) as required, enabling effective OOS operations.

[0059] The present invention may take many forms and modifications, and the specific embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the invention is not to be limited to the particular forms set forth in the detailed description, but rather to include all modifications and equivalents within the spirit and scope of the invention as defined.

We Claim

1. A LTCP mechanism (100) for autonomous capture of non-cooperative spacecraft, comprising:

   a LAM capturing unit (120) configured with a deployable frame (121) mounted on a servicer spacecraft (101) for initial soft capture of a LAM (122) of a client spacecraft (102);

   a telescopic unit (140) comprises a plurality of hollow tubes (143, 146) featured with a lead nut (144, 147) at the bottom of each tube, a central lead screw (142) and a three latch pins (145) for converting the rotary motion of an actuator (141) into the axial extending and retracting motion;

      wherein the plurality of hollow tubes (143, 146), each smaller in diameter than the previous one, allowing them to fit inside one another in a concentric manner;

   a compliant probe unit (160) rigidly mounted on the telescopic unit (140) comprises a cone-shaped probe (161), a probe flexure (163) for latching against a flexure spring (164) force and a SMA wire (166) to pull a wire rope (165) for unlatching the LAM (122) of the client spacecraft (102);

      wherein the latching is confirmed by a contact switch (162) in the compliant probe unit (160), the client spacecraft (102) pulled towards the servicer spacecraft (101) by the retracting motion of the telescopic unit (140) and disengage the deployable frame (121) and made them vertically rigid for preloading;

   a preloading unit (180) configured with a preloading surface (181) on the deployable frames (121) and a force sensor (182) for ensuring the desired preload and send signal to the actuator (141) to stop the retractable motion for initiating the OOS operations.

2. The LTCP mechanism (100) as claimed in claim 1, wherein the LTCP mechanism (100) has ability to capture the non-cooperative spacecraft in both GEO (1194 mm LAR) and LEO (937 mm LAR) types of spacecraft interface rings.

3. The LTCP mechanism (100) as claimed in claim 1, wherein the LTCP mechanism (100) configured with a robotic arm (103) and a stereo camera (104) to recognize the orientation of the client spacecraft (102) before capturing and monitor the engagement orientation of the servicer spacecraft (102) with the client spacecraft (101) during and after the capturing.

4. The LTCP mechanism (100) as claimed in claim 1, wherein the deployable frames (121) can perform both the initial soft capture of the LAM (122) and the final preloading of the client spacecraft (102) with the servicer spacecraft (101) using the single actuator (141).

5. The LTCP mechanism (100) as claimed in claim 1, wherein the soft capture by the deployable frames (121) ensures the spacecrafts (101, 102) do not move away from each other due to docking forces.

6. The LTCP mechanism (100) as claimed in claim 1, wherein the deployable frames (121) enabled with a MES sensor (105) to provide the cue for initiating soft capture in a non-contact manner.

7. The LTCP mechanism (100) as claimed in claim 1, wherein the deployable frames (121) are kept folded (stowed configuration) during launch and released once into the orbit to perform the necessary operations efficiently, resulting in compact storage.

8. The LTCP mechanism (100) as claimed in claim 1, wherein the deployable frames (121) are designed to avoid the need for an additional hold-down system by employing a non-back-drivable gear assembly driven by the actuator (141), thereby reducing mass, launch costs, and enhancing overall system reliability.

9. The LTCP mechanism (100) as claimed in claim 1, wherein the latch pins (145) are designed such that when the tube moves upwards, it latches to the next tube in contact, and when the tube moves downwards, it unlatches from the tube to which it was latched during the upward motion.

10. A method for axial extending and retracting motion achieved by the telescopic unit (140), comprising:

 for the extendable motion of the telescopic unit (140):

  the actuator (141) powers the lead screw (142) to rotate, causing the axial upward movement of the first tube (143) because the first tube lead nut (144) is engaged with the lead screw (142);

  once the first tube lead nut (144) reaches the end of the lead screw (142), the three latch pins (145) in the first tube (143) latch with the second tube (146) while the second tube lead nut (147) engages with the lead screw (142), causing the second tube (146) to move axially upwards;

  this sequence is repeated until the last tube reaches the end of the lead screw (142);

 for the retractable motion of the telescopic unit (140):

  the actuator (141) reverses the lead screw (142) rotation, causing the axial downward movement of the last tube (146) because the last tube lead nut (147) is engaged with the lead screw (142);

  once the last tube lead nut (147) reaches the shank of the lead screw (148), the lead nut of the next-to-last tube engages with the lead screw (142) while the three latch pins (145) unlatch from the last tube, causing the next-to-last tube to move axially downwards;

  this sequence is repeated until the first tube lead nut (144) reaches the bottom threaded portion of the lead screw (142).

11. The LTCP mechanism (100) as claimed in claim 1, wherein the telescopic unit (140) is used to insert the compliant probe unit (160) into the LAM (122) of the client spacecraft (102) during its extendable motion and to pull the client spacecraft (102) towards the deployable frames (121) mounted on the servicer spacecraft (101) during its retractable motion.

12. The LTCP mechanism (100) as claimed in claim 1, wherein the cone-shaped probe (161) moves in a guided manner inside the LAM (122) of the client spacecraft (102) due to its self-alignment capability.

13. The LTCP mechanism (100) as claimed in claim 1, wherein the LTCP mechanism (100) through the telescopic unit (140) has able to pull the client spacecraft (102) parallel to the servicer spacecraft (101) preloading surface (181) located on the deployable frames (121).

14. The LTCP mechanism (100) as claimed in claim 1, wherein the probe flexure (163) based latching and the SMA wire (166) based unlatching of the LAM (122) throat from the compliant probe unit (160) reduce the complexity and ensure a compact system.

15. The LTCP mechanism (100) as claimed in claim 1, wherein the force sensor (182) used to monitor the preload when the client spacecraft (102) butts onto the preloading surface (181) of the deployable frames (121).

16. A method for the autonomous capture of non-cooperative spacecraft using the LTCP mechanism (100), comprising:

    preparing the servicer spacecraft (101) for capture by collecting the data from the robotic arm (103) with the stereo cameras (104) and the MES sensor (105);

    initiating the soft capture of the LAM (122) of the client spacecraft (102) by moving the deployable frames (121) towards the LAM (122) surface;

actuating the telescopic unit (140) for extendable motion to insert the compliant probe unit (160) into the throat of the LAM (122);

latching the probe flexure (163) into the throat of the LAM (122) and disengage the deployable frames (121) from the LAM (121) and made them vertically rigid;

actuating the telescopic unit (140) for the retractable motion to pull the client spacecraft (102) towards the deployable frames (121) mounted on the servicer spacecraft (101);

ensuring the desired preload between the spacecrafts to stop the retractable motion and to initiate the OSS operations.

17. The LTCP mechanism (100) as claimed in claim 1, wherein after completing the OSS operations, the LTCP mechanism (100) has ability to push the client spacecraft (102) away from the servicer spacecraft (101), eliminating the need for a separate release mechanism.

18. The LTCP mechanism (100) as claimed in claim 1, wherein the LTCP mechanism (100) is capable of autonomously capture, preload, and release the client spacecraft repeatedly as required.

Dated this 13th Day of August 2024

Signature
-Digitally Signed-
Santosh Vikram Singh
IN/PA: 414
Agent For the Applicant

ABSTRACT

A NOVEL LAM THROAT CAPTURING & PRELOADING MECHANISM FOR AUTONOMOUS CAPTURE OF NON-COOPERATIVE SPACECRAFT

The present invention is the development of a novel LAM Throat Capturing and Preloading (LTCP) mechanism (100) for On-Orbit Servicing (OOS) to extend the life of non-cooperative spacecraft nearing end-of-life. The LTCP mechanism (100), integrated into a servicer spacecraft (101), comprises the LAM capturing unit (120), the telescopic unit (140), the compliant probe unit (160), and the preloading unit (180). It autonomously captures the client spacecraft (102) by soft capturing the LAM (122), inserting the compliant probe unit (160) for secure latching, and retracting the client spacecraft (102) for preloading. The mechanism ensures efficient use of mass, power, and space, and can repeatedly capture, preload, and release the client spacecraft (102) as required, enabling effective OOS operations.

Figure. 4.